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1.	Your Reference	P51068u GB
2.	Patent Application number *(The Patent Office will fill in this part)*	**0131003.6** 27 DEC 2001
3.	Full name, address and postcode of the or each applicant *(underline all surnames)*	Bookham Technology plc 90 Milton Park Abingdon Oxon OX14 4RY
	Patents ADP Number *(if you know it)*	
	If the applicant is a corporate body, give the country/state of its incorporation	England & Wales 07909757001
4.	Title of the invention	A Light Sensor
5.	Name of your agent *(if you have one)*	Fry Heath & Spence
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	The Old College 53 High Street Horley, Surrey RH6 7BN
	Patents ADP Number *(if you know it)*	05880273003

		Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
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Claim(s)	3
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Priority documents	xxx
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Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	~~yes~~
Request for preliminary examination and search *(Patents form 9/77)*	yes
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11. I/We request the grant of a patent on the basis of this application.

Signature S.G.U.

Date 24 December 2001

12. Name and daytime telephone number of person to contact in the United Kingdom — S. G. Unwin, 01865 841060

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A LIGHT SENSOR

This invention relates to a light sensor, in particular a light sensor for sensing an optical signal transmitted along a waveguide.

A variety of types of light sensors are known which can be mounted on an integrated optical circuit in order to receive light from a waveguide integrated on the circuit. One example is a SiGe/Si multi-quantum well (MQW) structure arranged to form a photodetector which can be mounted on a silicon optical circuit to receive an optical signal directed thereto by a waveguide.

The present invention aims to provide an alternative form of light sensor having advantages over such known light sensors.

According to the invention, there is provided an integrated optical waveguide having a light sensor integrally formed therewith comprising an integrated optical waveguide leading to a photodiode portion thereof, said portion being arranged to generate free charge carriers when light of one or more selected wavelengths is incident thereon and comprising a diode for detecting the presence of said free charge carriers.

Preferred and optional features of the invention will be apparent from the following description and from the subsidiary claims of the specification.

The invention will now be further described, merely by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic plan view of an in-line photodiode according to a preferred version of the invention;

Figure 2 is a cross-sectional view through a first embodiment of such an in-line photodiode;

Figure 3 is a cross-sectional view through a second embodiment of such an in-line photodiode;

Figure 4 is a cross-sectional view through a third embodiment of such an in-line photodiode;

Figure 5 is a cross-sectional view through a fourth embodiment of such an in-line photodiode;

Figure 6 is a plan view of another embodiment of an in-line photodiode according to the invention;

Figure 7 is a perspective view of a further embodiment of an in-line photodiode according to the invention;

Figure 8A is a perspective view of yet a further embodiment of an in-line photodiode according to the invention and Figure 8B is a cross-sectional view thereof; and

Figure 9 is a perspective view of another embodiment of a light sensor according to the present invention.

Figure 1 shows a waveguide 1 which forms part of an integrated optical circuit (not shown) formed on a planar substrate, e.g. a silicon chip. A first part 1A of the waveguide receives an input signal and transmits this to a portion of the waveguide which is arranged to provide an in-line photodiode 2 and a second part 1B of the waveguide receives the signal leaving the in-line photodiode 2 and directs this to an output.

In this embodiment, the in-line photodiode 2 is arranged to be partially transparent. It comprises one or more light absorptive regions which absorb

part of the signal being transmitted along the waveguide. In a typical arrangement, the absorptive regions may, for instance, absorb 5% or less of the signal being transmitted along the waveguide.

The degree of absorption of the signal may be controlled by the dimensions of the absorptive region, e.g. by its length along the waveguide and depth (perpendicular to the plane of the chip), and/or by controlling the absorption coefficient thereof.

The absorptive region may, for example, have a length in the range 100-1000 microns and a depth of around 0.1 microns.

The absorptive region is arranged to generate free charge carriers when light of one or more selected wavelengths is incident thereon and these are detected by a diode formed across or within the waveguide as will be described further below.

The absorptive region(s) may comprise any material which generates free charge carriers when light of one or more selected wavelengths is incident thereon. It may, for instance comprise a semiconductor material having a band gap of a size such that photons of a given wavelength (or shorter wavelengths) are able to excite charge carriers across the band gap from the valence band to the conduction band. Alternatively, it may comprise a semiconductor material whose band gap is too large for this to occur for the wavelength(s) of interest but in which deep band gap levels are formed between the conduction and valence bands to facilitate the generation of free charge carriers upon illumination by such wavelengths. It may also comprise light absorptive material such as polycrystalline or amorphous semiconductor materials.

Deep band gap levels have energy levels which differ from the energy levels of the valence band or conduction band by an amount which is too great for

thermal excitation of the electrons therein to give rise to any significant level of dark current.

Examples of suitable absorptive materials include: Si/Ge alloys, Ge-rich regions within a silicon matrix, polycrystalline silicon, amorphous silicon, iron silicide, etc.

In some cases, the absorptive region may be arranged to absorb a specific wavelength or wavelength band, e.g. wavelengths of around 1.3 and/or 1.5 microns (as commonly used in telecommunication applications), in other cases the absorptive region may be capable of absorbing a wider range of wavelengths.

The absorptive region(s) is selected so as to be suitable for being integrally formed with or in the waveguide. This greatly facilitates the manufacture of the light sensor as it is then not necessary to hybridise the light sensor as a separate component onto the optical circuit.

The following examples relate to light sensors integrated on a silicon substrate but the principle is applicable to other types of substrate, e.g. in III-V compounds such as InGaAsP or InP.

Figures 2-5 shows cross-sections through in-line photodiodes formed within rib waveguides 10 fabricated in an optically conductive silicon layer 11. Preferably, the silicon layer 11 is separated from a supporting substrate 12 (typically also of silicon), by an optical confinement layer 13 (typically of silicon dioxide). Such a structure is conveniently formed from a silicon-on-insulator chip (as widely used for integrated electrical circuits).

Figure 2 shows an absorptive region 14 formed within a rib 10A of the rib waveguide 10, the rib projecting from a slab region 10B formed within the silicon layer 11.

In this example, the absorptive region 14 is spaced from the upper surface of the rib 10A leaving a silicon buffer region 10C therebetween to provide the desired overlap between the absorptive region 14 and the optical mode transmitted along the waveguide (the approximate location of the wavefront of a signal guided by the rib waveguide is shown by dashed lines 16). An oxide layer 15 is provided over the silicon layer 11 for passivation.

When an optical signal is transmitted along the waveguide, part of the signal will be absorbed by the absorptive region 14. This generates free charge carriers within the waveguide and these are detected by a lateral pin diode formed across the waveguide. The pin diode comprises a p-doped region 17 and an n-doped region 18 formed in the silicon layer 11 on opposite sides of the rib waveguide with a nominally intrinsic region therebetween. Metal contacts 19 and 20 are provided to provide electrical connection to the p- and n-doped regions 17 and 18, respectively.

Pin diodes are known for injecting charge carriers into a waveguide to alter its refractive index and to attenuate optical signals therein but in this case the pin diode is used to collect charge carriers generated by the partial absorption of an optical signal by absorptive region 14 and thus provide an electrical signal indicative of the optical signal within the waveguide.

In the embodiment shown, the p and n-doped regions 17 and 18 are formed beneath recesses 21 and 22 formed in the silicon layer 11. This helps ensure the p- and n-doped regions extend through the silicon layer 11 to the oxide layer 13 and it allows a smaller structure to be formed without increasing optical losses caused by the presence of the doped regions adjacent the waveguide. The collection efficiency of the photogenerated charge carriers is also improved (as is the speed of the device) by reducing the distance between the absorptive region 14 and the doped regions 17 and 18.

The dimensions of a waveguide are typically in the range 2-10 microns so the distance the charge carriers have to move to be collected by the p- or n-doped regions 17 and 18 from the locations where they are generated (in the absorptive region 14) is typically 10 microns or less in such arrangement and preferably 5 microns or less. This not only increases the speed of the device, i.e. the time between the optical signal being received by the absorptive region and the generation of an electrical signal across the pin diode is very short, but also reduces the opportunity for impurities or other materials in the silicon layer from absorbing the charge carriers (and thus preventing them from reaching the p- or n- doped regions 17 and 18).

If the light sensor is intended to monitor the signal being transmitted along the waveguide, the absorptive region 14 is preferably located in a position where it only partially overlaps the optical mode 16. In the illustrated example, the absorptive region 14 is located within the rib 10A towards the uppermost portion thereof. Alternatively, or additionally, one or more absorptive regions could be provided in the slab region 10B on one or both sides of the rib waveguide, i.e. between the rib 10A and the doped region 17, 18, or at the bottom of the silicon layer 11 adjacent the oxide layer 13.

In other arrangements, the absorptive region may be positioned so as to maximise the overlap with the optical mode.

Figure 3 shows an alternative arrangement which is similar to that of Figure 2 except that the pin diode is formed between p-doped regions 30, 31 on one or both sides of the rib waveguide 10 and an n-doped region 32 provided in the upper surface of the rib 10A (or vice versa). Such a vertical arrangement may be more appropriate with thicker waveguides (measured perpendicular to the plane of the chip).

In another alternative, the absorptive region 14 may comprise a SiGe layer, e.g. formed by selective epitaxial growth of the rib 10A. Similarly, other types

of absorptive regions 14 may be used, e.g. Ge-rich islands, Si-amorphous regions, $FeSi_2$, defect regions (e.g. caused by implantation of Si ions or other ions such as gold, oxygen, hydrogen or helium) etc.

Defects formed by ion implantation can be engineered by controlling the dose and subsequent annealing. Further details of such defect engineering are given in the applicant's co-pending application No. .... entitled "A Photodiode" filed on the same day as the present application the disclosure of which is incorporated herein.

If amorphous silicon is used as the absorptive region 14, this may be provided at the upper portion of the rib 10A, without the intervening layer 10C of silicon. A layer of amorphous silicon can be fabricated in the rib 10A by ion implantation.

Amorphous silicon absorbs light at a wavelength of 1.55 microns and the dimensions of the amorphous layer, i.e. its thickness and/or length, can be adjusted to provide the required degree of absorption.

Figure 4 shows a cross-section through another embodiment which uses metallised areas to provide Schottky contacts which provide electron-hole pairs from internal photoemission. Light transmitted along the waveguide is incident upon the metallised areas (as these are provided on the walls of the waveguide) and provides charge carriers within the metal layer with sufficient energy to pass over the Schottky barrier formed between the metal layer and the semiconductor material of the waveguide so releasing charge carriers within the waveguide. As in the earlier embodiment, these are then detected by a pin diode. In the arrangement shown in Figure 4, a vertical pin diode is provided between p-doped regions 40, 41 on one or both sides of the rib waveguide and the metallised layer 42 provided on the upper surface of the rib. The metallised layer 42 thus serves both to form a Schottky barrier with

the semiconductor waveguide and as an electrical terminal of the pin diode for detecting the charge carriers generated within the device.

The polarisation dependence of such a device can be controlled by adjusting the dimensions of the metallised area 42. In another arrangement, the metallised area may partially cover both the upper and side surface(s) of the rib 10A as shown in the embodiment illustrated in Fig 5.

Another alternative is to interdigitate the metal contacts as shown in the plan view in Figure 6. A first set of metallised areas 50 are provided on the upper surface of the rib 10A and a second set of metallised areas 51 are provided on both the upper and side surfaces of the rib 10A (or just on the side surface(s) thereof). The length of the metallised areas in each set can be selected to balance the TE and TM absorption by the metal contacts.

Figure 7 is a perspective view of an in-line photodiode comprising a rib waveguide 60 made of a first material, e.g. silicon, having a portion 61 integrally formed therewith made of a second material, e.g. a silicon germanium alloy. The first material has a band gap which is too large for electrons excited by photons of the incoming light signal to move into the conduction band. However, the second material is selected to have a smaller band gap so that photons of the wavelength of light to be detected are able to move into the conductive band. The second material is chosen so as to enable said portion to be integrally formed with the remainder of the waveguide. The second material may, for instance, be formed by diffusing in another material, e.g. Ge, and then heat treating the portion to form an alloy between the finished seal materials, the composition of said alloy being selected to have a lower band gap than that of the first material alone. Alternatively, a portion of the silicon waveguide can be etched away and a portion comprising a silicon-germanium alloy grown or deposited in its place. It will be apparent that the alloy should be such as to be integrally formed with the adjacent portion of the waveguide albeit with some mis-match at the

boundry therebetween due to the different materials. A pin diode is provided to detect the charge carriers generated in the Si/Ge portion of the waveguide. In the example shown, the pin diode is formed along the length of the waveguide, i.e. with a p- doped region 62 formed in a part of the waveguide leading to the Si/Ge portion and an n-doped region 63 formed in a part of the waveguide downstream of the Si/Ge portion. Such an in-line pin diode will have low efficiency due to absorption of the optical signal by the p- and n-doped regions 62 and 63 but this may be tolerated in applications in which the light sensor is merely required to sense the optical signal without the need for the signal to pass therethrough to other devices. Indeed, in some cases, the downstream doped region 63 may be extended so as to ensure that it absorbs substantially all of the light signal received thereby, i.e. so as to form a beam dump downstream of the light sensor.

In other arrangements, particularly when it is required for at least a substantial part of the signal to pass through the device, a lateral or vertical pin diode arrangement such as those described above may be used.

Figures 8A and 8B show an arrangement having a lateral pin diode formed across a waveguide 70, p- and n- doped regions 71 and 72 being provided in the slab regions 74 on either side of the rib waveguide 70 a portion 73 of which, between the p- and n- doped regions 71 and 72, is formed of a Si/Ge alloy.

Figure 9 is a perspective view of another embodiment having a Schottky barrier for generating charge carriers within a waveguide 80. In this case, a metallised region 81 is provided on the end face of a rib waveguide (and surfaces of the waveguide adjacent the end face). Light transmitted along the waveguide 80 and incident on this metallised layer 81 gives rise to the photoemisson of charge carriers into the end of the waveguide. P- and n-doped regions 82 and 83 form a lateral pin diode across the waveguide to detect these charge carriers. The metal layer 81 may, for instance, be formed

of platinum. A Schottky barrier is thus formed between the platinum and a layer of platinum silicide that arises at the end of the silicon waveguide 80.

A further advantage of the in-line photodiodes described above is that they have low polarisation dependency. Even if the materials used have significant birefringence, if the waveguide has a similar confinement factor for both the TE and TM modes (the confinement factors being determined by the refractive index and geometry of the waveguide) the photodiode can be made substantially polarisation independent.

In the embodiments described above, the in-line photodiode is of the same width as the waveguide leading to and from it. However, in some cases, it may be desirable to form the photodiode portion of a different width (either wider or narrower) and provide transitional, tapered regions leading thereto.

The arrangements described above provide a number of advantages as indicated below:

(i) the light sensor region is automatically aligned with the waveguide leading thereto as it is formed within the waveguide.

(ii) There is no possibility for the light sensor region to subsequently move out of alignment with the waveguide (as can happen with a hybridised light sensor).

(iii) The light does not have to pass through interfaces or epoxy between the waveguide and the light sensor.

(iv) Fabrication is easier as the light sensor can be formed by standard lithographic techniques and a separate component does not have to be mounted and secured to the chip.

(v) The device is more rugged as it is of an integral construction.

When the arrangement is used to monitor a signal being propagated along a waveguide it also has the advantage that the proportion of light absorbed by the sensor can be accurately determined by the fabrication thereof and the fabrication techniques used are highly repeatable. This is in contrast to conventional arrangements used to tap off part of a signal, e.g. using directional couplers, Y-junctions etc. and measuring the tapped off signal. Such devices are highly sensitive to fabrication tolerances which have a significant effect upon the proportion of light that is tapped off.

CLAIMS

1. According to the invention, there is provided an integrated optical waveguide having a light sensor integrally formed therewith comprising an integrated optical waveguide leading to a photodiode portion thereof, said portion being arranged to generate free charge carriers when light of one or more selected wavelengths is incident thereon and comprising a diode for detecting the presence of said free charge carriers.

2. A waveguide as claimed in claim 1 wherein said portion comprises one or more regions of light absorbing material formed within the waveguide.

3. A waveguide as claimed in claim 2 in which the light absorbing material is an amorphous or polycrystalline material.

4. A waveguide as claimed in claim 3 in which the amorphous or polycrystalline material is doped.

5. A waveguide as claimed in claim 2 in which the light absorbing material is an alloy.

6. A waveguide as claimed in claim 2 in which the light absorbing material includes defects which provide deep band gap states within the band gap thereof.

7. A waveguide as claimed in any preceding claim formed of silicon, preferably formed within a silicon-on-insulator chip.

8. A waveguide as claimed in claims 3 and 7 in which the absorbing material is amorphous silicon or polycrystalline silicon.

9. A waveguide as claimed in claims 5 and 7 in which the alloy is a silicon-germanium alloy.

10. A waveguide as claimed in claim 6 and 7 in which the deep band gap states are formed by ion implantation.

11. A waveguide as claimed in claim 1 in which said portion comprises one or more metallised areas which form a Schottky barrier with the material of the waveguide.

12. A waveguide as claimed in claim 111 in which the metallised areas comprise platinum, aluminium or titanium.

13. A waveguide as claimed in any preceding claim in which said portion is partially transparent, the diode being arranged to monitor the optical signal being propagated along the waveguide.

14. A waveguide as claimed in claim 13 in which said portion absorbs 5% or less of the optical signal propagated along the waveguide.

15. A waveguide as claimed in any preceding claims in which the diode comprises a pin diode.

16. A waveguide as claimed in claim 15 in which the pin diode is a lateral pin diode.

17. A waveguide as claimed in claim 15 in which the pin diode is a vertical pin diode.

18. A waveguide as claimed in any preceding claim which is a rib waveguide comprising a rib projecting from a slab region.

19. A waveguide as claimed in claim 18 and claim 16 or claim 17 in which p-doped and/or n-doped regions of the pin diode are formed at the base of one or more recesses formed in the slab region.

20. A waveguide as claimed in claim 2 and claims 18 or 19 in which said one or more regions are provided within the rib of the rib waveguide.

21. A waveguide as claimed in claim 11 and claim 18 or 19 in which said one or more metallised areas are provided on one or more side or top faces of the rib.

22. A waveguide as claimed in any preceding claim in which said portion is arranged to absorb substantially all the light received thereby so as to also act as a beam dump.

23. A waveguide as claimed in any preceding claim in which the refractive index of the material thereof and/or the dimensions thereof are selected so as to provide similar confinement factors for both the TE and TM modes whereby the detection of light thereby is substantially polarisation independent.

24. A waveguide substantially as hereinbefore described with reference to and/or as shown in one or more of the accompanying drawings.

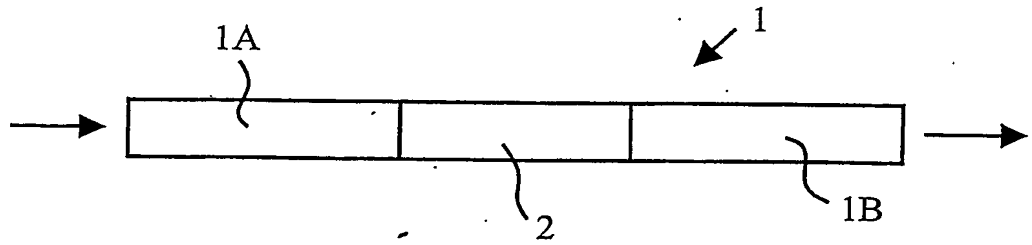

Figure 1

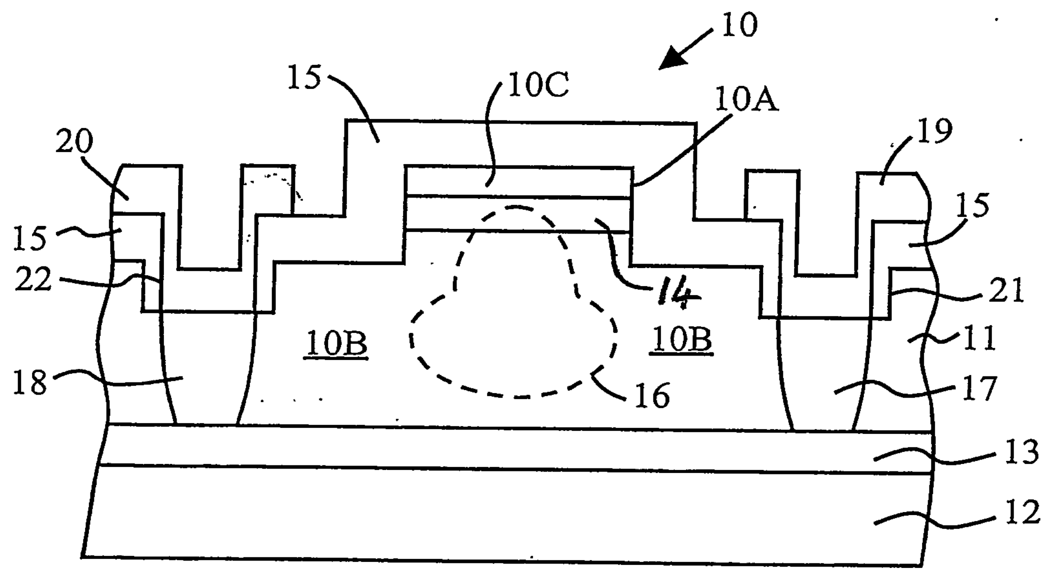

Figure 2

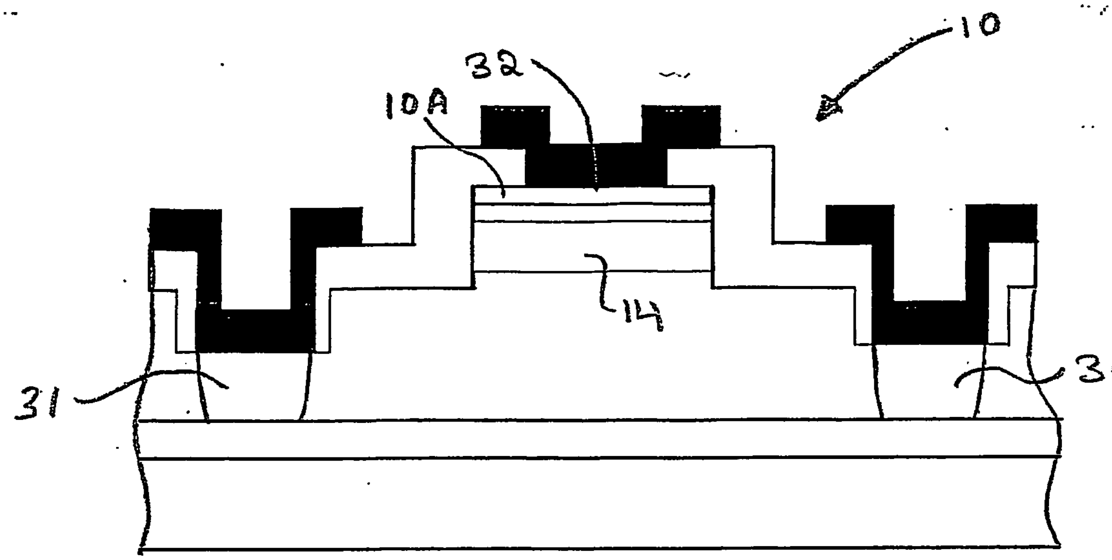

figure 3

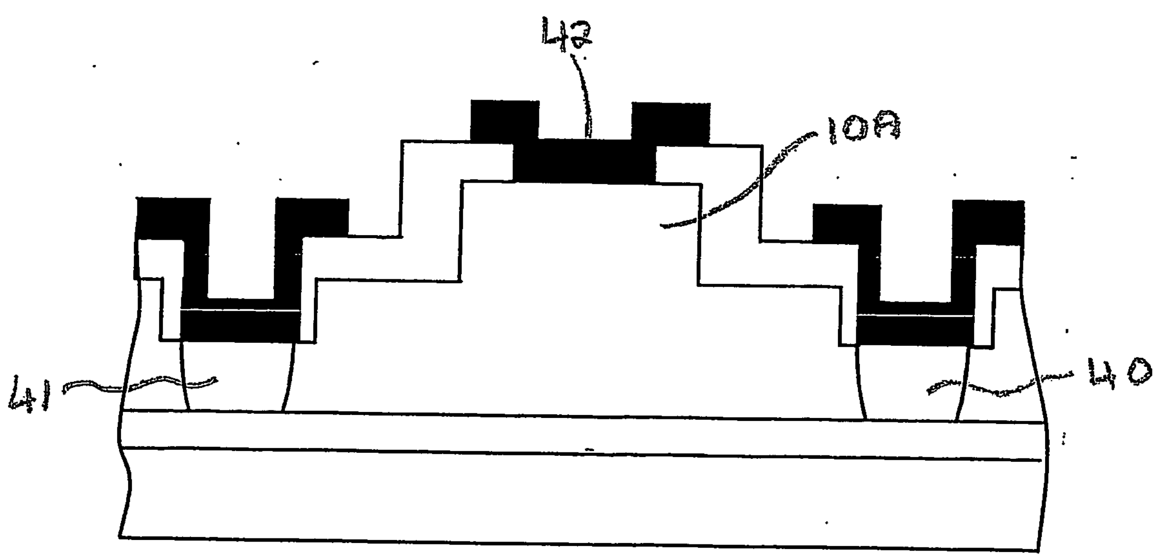

Figure 4

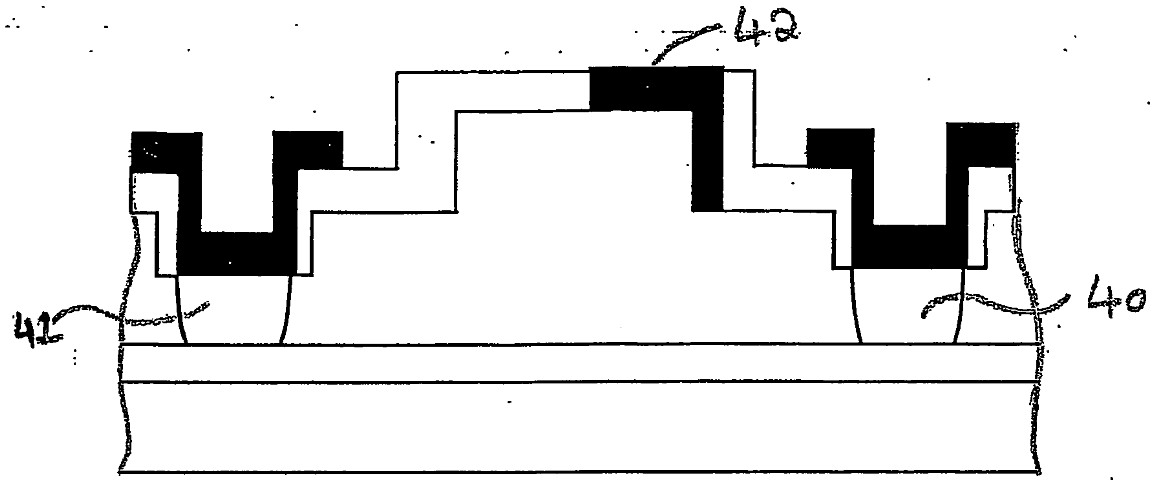

Figure 5

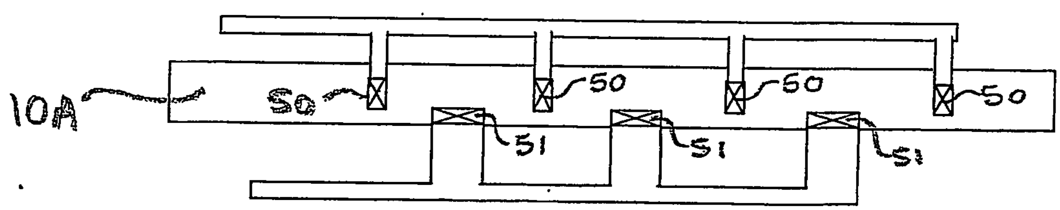

Figure 6.

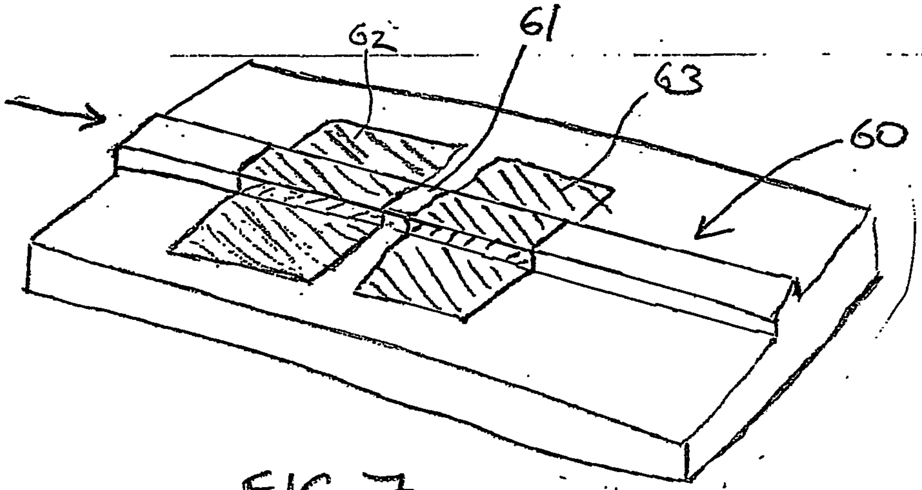

FIG. 7.

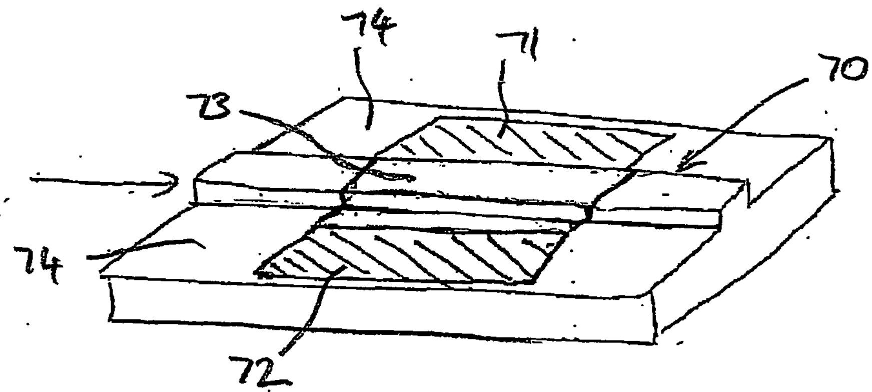

FIG. 8A.

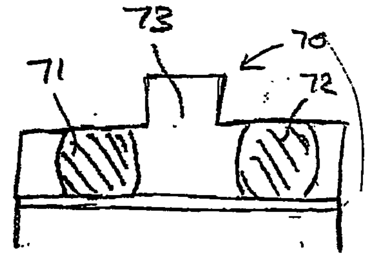

FIG. 8B.

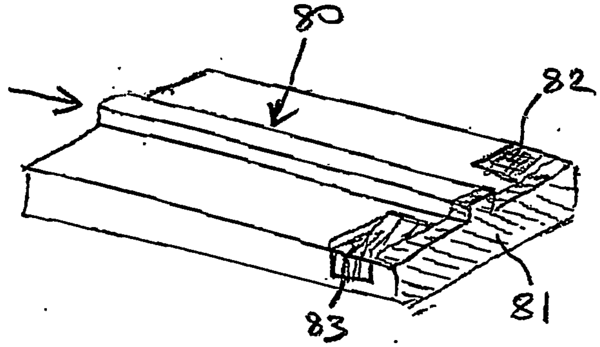

FIG. 9.